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Editorial

EEG coherence

Coherence between pairs of electroencephalogram signals (EEG) recorded simultaneously from different scalp sites provides a high time resolution measure of the degree of dynamic connectivity between brain regions. We would like to thank Dr. John Andreassi, editor of the *International Journal of Psychophysiology*, for the opportunity to present this special issue on coherence studies of the EEG. The issue is an outgrowth of the symposium 'EEG Coherence Studies on Cognition and Working Memory' presented at the 11th World Congress of Psychophysiology held in Montreal in 2002, chaired by the guest editor. All of the papers were peer-reviewed in accord with *Journal* standards, and we would like to acknowledge and thank the reviewers and authors for their contributions. This special issue is dedicated to the memory of Drs. Baerbel Schack and Astrid von Stein, who have made outstanding contributions to EEG coherence research. Their leadership in the field of EEG coherence studies is sorely missed.

Coherence measures the correlation between a pair of signals as a function of frequency. Thus it provides a means for identifying and isolating frequency bands at which the EEG displays between-channel synchronization. Both intrinsic and extrinsic narrow band rhythms occur in the EEG, with each rhythm having a characteristic functional significance and topographic distribution. Consequently coherence functions are particularly apt means for extracting from the EEG information bearing upon processes that have a role in mediating connectivity among brain regions.

Coherence of a signal pair at a given frequency can be conceptualized as 1) passing each signal through a narrow band filter tuned to the given frequency, 2) computing the Pearson-product moment correlation coefficient of the filtered signals, and 3) squaring the resulting correlation coefficient. The amplitudes of coherence functions range from a minimum of zero to a maximum of +1.0. In formal terms, the coherence function is defined as the squared magnitude of the cross-spectral density of the signal pair divided by the product of the power spectra of the two signals. This is expressed in Eq. (1), where the coherence at frequency f between signals 1 and 2 is denoted by $C_{12}(f)$, the cross-spectrum of signals 1 and 2 is denoted by $W_{12}(f)$, and the respective power spectra of the two signals are denoted by $W_{11}(f)$ and $W_{22}(f)$.

$$C_{12}(f) = \frac{|W_{12}(f)|^2}{W_{11}(f)W_{22}(f)}. \quad (1)$$

Interest in utilizing EEG coherence developed about 40 years ago. The earliest publication on this topic that we have been able to find was an abstract of a talk on relationships between EEG signals given by D.O. Walter (1968) at the June, 1967 American Electroencephalographic Society Meeting. The first full paper was Gersch and Goddard's (1970) report on the use of coherence and partial coherence to infer the locations of epileptic foci. The number of published studies of EEG coherence was sparse over the next decade, but since has increased markedly. Over the last 15 years there have been numerous reports of studies in which EEG coherence was utilized in investigating cognitive issues, such as the study of networks involved in working memory operations, linguistic functions and binding. The articles in this issue are examples of the application of EEG coherence to the study of working memory and language processes.

Sarnthein, Morel, von Stein, and Jeanmonod utilized intracranial and scalp recordings obtained during surgery from patients with neurological disorders to investigate thalamocortical and within-thalamus interactions at rest and during a task with increased working memory demand (counting backwards). They found generally high levels of coherence between scalp EEG and thalamus local field potentials in the theta band, which fits with the concept of thalamocortical loops. The authors carried out bicoherence analyses of the thalamic local field potentials; essentially a between frequency bands form of correlation performed on the activity recorded from a single electrode. Increased synchronization was found between activity in the theta and beta bands as working memory demand increased, which was indicative of interactions between thalamic generators of theta and beta activity. For obvious reasons, coherence studies such as Sarnthein et al.'s are rare. Sarnthein et al. show, however, that coherence analyses of

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such data can be used to extend our knowledge of basic properties of neural systems.

Sauseng, Klimesch, Shabus, and Doppelmayr studied neural networks involved in mediating executive operations in a visual-spatial working memory task with two levels of task difficulty. The easier task required mentally imaging abstract patterns. The more difficult task required mentally manipulating the patterns, thereby more heavily engaging working memory executive operations. It is thought that working memory central executive operations are based, in part, upon frontal cortex networks, while storage-representational operations depend more upon posterior cortex. Working memory functions are due to interactions between the frontal central executive and posterior storage systems. Sauseng et al. tested this concept by examining patterns of coherence between EEG recordings from frontal and posterior scalp sites. They found that as task difficulty increased, presumably requiring more executive resources, coherence between frontal and posterior theta activity increased. They also found that the increased demand for executive resources was accompanied by decreased coherence in the alpha band among EEG recordings from frontal sites. The theta band findings support the concept of frontal and posterior cortex interactions as a part of working memory operations, with tighter connectivity as task difficulty increases. Although the alpha band findings of decreased connectivity between frontal sites as task difficulty increased is not as readily interpreted, nevertheless, the scalp location of the alpha band effect was consistent with the idea that executive working memory operations involve frontal cortex.

Schack, Klimesch, and Sauseng studied alpha and theta band coherence during a Sternberg-type short-term memory scanning task. They investigated both within-band, between electrode sites and *between-bands*, between electrode sites synchronization. The latter type of coherence analysis, between electrode sites and between-bands, is a recent development in EEG methodology. As in the Sauseng et al. article, one of the premises was that frontal theta activity is associated with executive functions and posterior alpha activity is associated with short-term storage operations. Schack et al. found that increased memory load was accompanied by increased alpha activity during both the retention and retrieval stages of the memory scanning task, while theta activity only increased with memory load during the retrieval stage. These findings fit with the concept that retention may involve relatively low demands upon the central executive, but accessing the maintained information for further processing depends crucially upon the central executive. Findings of significant between-band alpha and theta synchronization further indicated an interplay between the mechanisms that underlie alpha and theta activity, which fits with the thalamic bicoherence results in the Sarnthein et al. article.

Haarmann and Cameron used coherence to analyze working memory operations in a linguistic task. The meaning of a sentence was retained in short-term memory during a delay interval that followed sentence presentation and ended with a test of the accuracy with which the meaning was retained. Task demand was varied factorially by manipulating the syntactic complexity of the sentence and the degree of semantic relatedness among the nouns in the sentence. Syntactic complexity and semantic relatedness interacted, with a significant increase in error rate when both syntactic complexity was high and the nouns were unrelated. The relative amplitudes of theta and alpha activity were reversed in the sentence processing and retention intervals, with theta being dominant during sentence processing and, as in the Schack et al. article, alpha being dominant during retention. During sentence processing, the coherence in the theta band of anterior-to-posterior electrode pairs increased significantly over the coherence in the pre-sentence baseline interval, and then became sparse during retention. In contrast, coherence in the alpha-band was negligible during sentence processing, but during retention coherence between anterior–posterior electrode pairs was significantly greater than in the pre-sentence baseline and sentence processing intervals. When both syntactic complexity was high and semantic relatedness was low, alpha band coherence during retention, but not the level of alpha activity, was increased in comparison with the other three combinations of syntactic and semantic demand. These theta and alpha band findings were consistent with those from the Sauseng et al. and Schack et al. articles, in that activity in the theta band appeared to be associated with controlled processing that made high demands on the central executive, while alpha band activity appeared to be a concomitant of retention. Haarmann and Cameron remarked that rather than reflecting mental idling, alpha band activity during retention may index an inner direction of attention, way from the external environment, thereby minimizing disturbances that might interfere with the retention process.

Weiss, Mueller, Schack, King, Kutas, and Rappelsberger conducted an exploratory study of the temporal dynamics of theta, beta, and gamma activity during processing of two types of sentences with different levels of complexity. Both sentences had a relative clause embedded between the subject and verb of the main clause. In the less complex (and more easily processed) sentences, the subject of the main clause was also the subject of the relative clause. In the more complex sentences, the subject of the main clause was the object of the relative clause. Weiss et al. analyzed the effects of sentence complexity upon coherence between anterior–posterior regions, within the anterior region and within the posterior region. They utilized an auto-regressive moving average (ARMA) technique to obtain continuous high time resolution (4 ms) estimates of coherence with a narrow band frequency resolution (0.5 Hz) over the entire time-course of

the sentences. ARMA techniques have been widely used for dynamic estimates of power spectra. Weiss et al. are among the first to apply ARMA to the estimation of EEG coherence. They found that EEG coherence varied as a function of sentence complexity, with different frequency bands being affected in the relative clause and post-relative clause intervals, respectively. During the relative clause, the effect of sentence complexity upon coherence was largest and most wide spread in the gamma band. Theta and beta band coherences were most sensitive to complexity in the post-relative clause interval. Given the exploratory nature of the Weiss et al. study, it is too soon to formulate a definitive interpretation of their findings. Rather, the authors offer an extensive discussion of how their findings relate to event-related potential and other EEG studies of processing sentences with embedded relative clauses.

Ford, Gray, Faustmann, Heinks, and Mathalon used gamma band coherence to investigate how frontal speech-generation systems communicate with temporal speech-perception systems when a subject is talking. At issue was whether the synchrony involved in connecting frontal and temporal systems differed between passive listening as opposed to the subjects monitoring their own speech. For further insight into the monitoring process, Ford et al. compared the coherence obtained when the sound heard by a subject was a distortion of the subject's speech with the coherence obtained when there was no distortion. The issue here was whether gamma band synchronization was involved in a feedback system for producing compensatory operations if what was heard was not the same as what was spoken. They found that gamma band coherence was larger during talking in comparison with listening, and that the coherence was reduced if the sound heard by a subject was a distortion of the subject's speech. Ford et al.'s findings support the idea that self-speech monitoring involves gamma band connectivity between frontal speech-production and temporal speech-perception systems, and is an example of how studies have gone beyond establishing properties of synchronization measures to making specific inferences about operations of neural systems.

1. Some remarks on methodology

Confounding the effects of volume conduction with between site synchronization effects is an ever present problem for interpreting coherence measurements. Occasionally the data may have fortuitous properties that can be used to rule out volume conduction as an explanation for between conditions change in coherence (e.g., if EEG power did not change). In general, however, more in the way of experimental design and data analysis procedures will be required. There are a number of strategies for minimizing such confounds. Suitably arranged electrode montages or transforming the electric field measurements into current source densities can reduce the putative contribution of volume conduction to coherence measurements. Approaches along these lines have been examined in detail by Srinivasan et al. (1998) and Nunez et al. (1999) and their papers provide a useful starting point for devising strategies to deal with volume conduction confounds.

Nolte et al. (2004) recently reported an interesting possibility for eliminating volume conduction effects from coherence measurements. They reasoned that because volume conduction is effectively instantaneous, there should be no between-electrode phase lag for volume conduction activity. Consequently volume conduction only contributes to the real (in phase) part of power cross-spectra. Thus, if the coherence measure is modified so that the real part of the cross-spectrum is discarded, and only the imaginary (90° out of phase) part is used, volume conduction effects would be eliminated. Although not likely to be a universal panacea for the volume conduction confound, in some cases this approach may be useful. The drawback to eliminating the real part of the cross-spectrum is that some non-volume conduction activity may also be eliminated, leading to a loss of statistical power.

Analysis of coherence from scalp recorded EEG only can provide, at best, rough estimates of the locations of the brain regions whose connectivity is responsible for EEG synchrony observed on the scalp. Hoechstetter et al. (2004) introduced a dipole source approach in an attempt to obtain improved estimates of within-brain connectivity. While much remains to be done in determining the accuracy and effective utility of such an approach, interested readers may wish to examine the Hoechstetter et al. paper.

References

Gersch, W., Goddard, G.V., 1970. Epileptic focus location: spectral analysis method. Science 169, 701–702.

Hoechstetter, K., Bornfleth, H., Weckesser, D., Ille, N., Berg, P., Scherg, M., 2004. BESA source coherence: a new method to study cortical oscillatory coupling. Brain Topography 16, 233–238.

Nolte, G., Bai, O., Wheaton, L., Mari, Z., Vorbach, S., Hallet, M., 2004. Identifying true brain interaction from EEG data using the imaginary part of coherency. Clinical Neurophysiology 115, 2292–2307.

Nunez, P.L., Silberstein, R.B., Shi, Z.P., Carpenter, M.R., Srinivasan, R., Tucker, D.M., et al., 1999. EEC coherency: II. Experimental comparisons of multiple measures. Clinical Neurophysiology 110, 469–486.

Srinivasan, R., Nunez, P.L., Silberstein, R.B., 1998. Spatial filtering and neocortical dynamics: estimates of EEG coherence. IEEE Transactions on Biomedical Engineering 45, 814–827.

Walter, D.O., 1968. Coherence as a measure of relationship between EEG records. Electroencephalography and Clinical Neurophysiology 24, 282.

Daniel Ruchkin
Cognitive Neuroscience Section,
National Institute of Neurological Disorders and Stroke,
Bethesda, MD, USA
E-mail address: druchkin@mindspring.com.